RECENT ADVANCES IN NDE AND SHM OF BRIDGE SUPERSTRUCTURE WITH SONIC AND RADAR METHODS

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ABSTRACT

Results are presented for nondestructive evaluation (NDE) of concrete bridge girders and decks with sonic Impact Echo Scanning with a handheld scanner and bridge deck scanner, respectively. Structural health monitoring (SHM) to measure displacements and vibrations with non-contacting interferometric phase radar is illustrated for a post-tensioned segmental bridge span

INTRODUCTION

The use of Impact Echo Scanning (IES) allows for much more rapid and closely-spaced sonic testing of concrete bridge girders and decks than was previously possible with sonic methods. Specific IES applications to date include the following: 1. checking for areas of poorly grouted and voided ducts that increase the risk of corrosion of post-tensioning tendons, 2. concrete bridge deck scanning to identify areas of delamination and cracking damage due to rebar corrosion for repairs, and 3. bridge deck scanning to check for areas of internal void/honeycomb, concrete integrity and thickness. The use of interferometric phase radar with the IBIS-S system allows for rapid monitoring and load testing of bridges by precise measurements of vertical displacements under known loads to a precision of up to 0.0004 inches (0.01 mm) and vibration frequencies from 0 to 100 Hz. The use of the IBIS-S system is illustrated for a new, post-tensioned concrete segmental bridge.

IMPACT ECHO SCANNING

Background of the Impact Echo Technique

The Impact-Echo test involves dynamically exciting a concrete structure with a small mechanical impactor and measuring the reflected wave energy with a displacement transducer. The resonant echoes in the displacement responses are usually not apparent in the time domain, but are more easily identified in the frequency domain. Consequently, linear amplitude spectra of the displacement responses are calculated by performing a Fast Fourier Transform (FFT) analysis to determine the resonant echo peak frequencies in the frequency domain from the displacement transducer signals in the time domain. The relationship among the echo frequency peak f, the compression wave velocity V_P, and the echo depth *D* is expressed in the following equation:

$$D = \beta V_p/(2*f) \quad (1)$$

where β is a shape factor which varies based on geometry. The value of β is approximately 0.96 for a concrete slab/wall shape (1).

Impact Echo Scanner

The Impact-Echo Scanner (IES) was first conceived by the author of this paper and subsequently researched and developed as a part of a US Bureau of Reclamation prestressed concrete cylinder pipe integrity research project (2). This technique is based on the Impact-Echo method (1,3). In general, the purpose of the Impact-Echo test is usually to either locate delaminations, honeycombing or cracks parallel to the surface or to measure the thickness of concrete structures with typically one-sided access for testing (pavements, floors, retaining walls, tunnel linings, buried pipes, etc.). To expedite the Impact-Echo testing process, an Impact-Echo scanning device has been developed with a rolling transducer assembly incorporating multiple sensors. When the test unit is rolled across the testing surface, an opto-coupler on the central wheel keeps track of the distance. This unit is calibrated to impact and record data

at intervals of nominally 25 mm (1 inch). The maximum frequency of excitation of the solenoid impactors in the scanner is 25 kHz. The impactor in scanner can be replaced for an impactor that generates higher frequency. Typical scanning time for a line of 4 m (13 ft), approximately 160 test points, is 60 seconds. In an Impact-Echo scanning line, the resolution of the scanning is about 25 mm (1 inch) between IE test points. Research on the sensitivity of the IES device in the detection of voided vs. grouted ducts has been previously reported (4,5). Raw data in the frequency domain are first digitally filtered using a Butterworth filter with a band-pass range of 2 kHz to 20 kHz. Automatic and manual picks of dominant frequency were performed on each spectrum and an Impact-Echo thickness was calculated based on the selected dominant frequency. A three-dimensional plot (in either color or grayscale) of the condition of the tested specimens can also be generated by combining the calculated Impact-Echo scan lines.

Case History on the Orwell Bridge in England

This section presents an example case history using the Impact Echo Scanner to locate anomalies inside post-tensioned bridge ducts inside the Orwell Bridge in England. The testing was conducted typically from inside the bridge rolling vertically up the web walls with the IES system. The tests were typically performed every 2 meters (m) along a web wall and each vertical scan generally started from the bottom inside chamfer and ran to the top inside chamfer of the tested web walls for about 72 tests over 1.8 m of wall. The results from the tests are presented in a thickness tomogram fashion for each web wall for each tested span. Example test results from one of the spans are presented in Figures 1 and 2 (shows IES unit) which reveal discontinuities or voids located at 20 m from Pier 2 and from the bottom of the wall (location where the scan started) to a height of 0.6 m. The IE records indicated cracks/voids at depths of 12 – 15 cm from the test surface. In addition, the plots also indicate a thicker area (presented in black color) representing voids inside the duct(s) located at 42 m from Pier 2 and from heights of 0.9 – 1.15 m. The color map in Figure 1 shows normalized thicknesses (the IE thickness divided by the nominal thickness at the tested line as the walls varied from 32 to 65 cm in thickness) by color from 0.1 to 1.3.

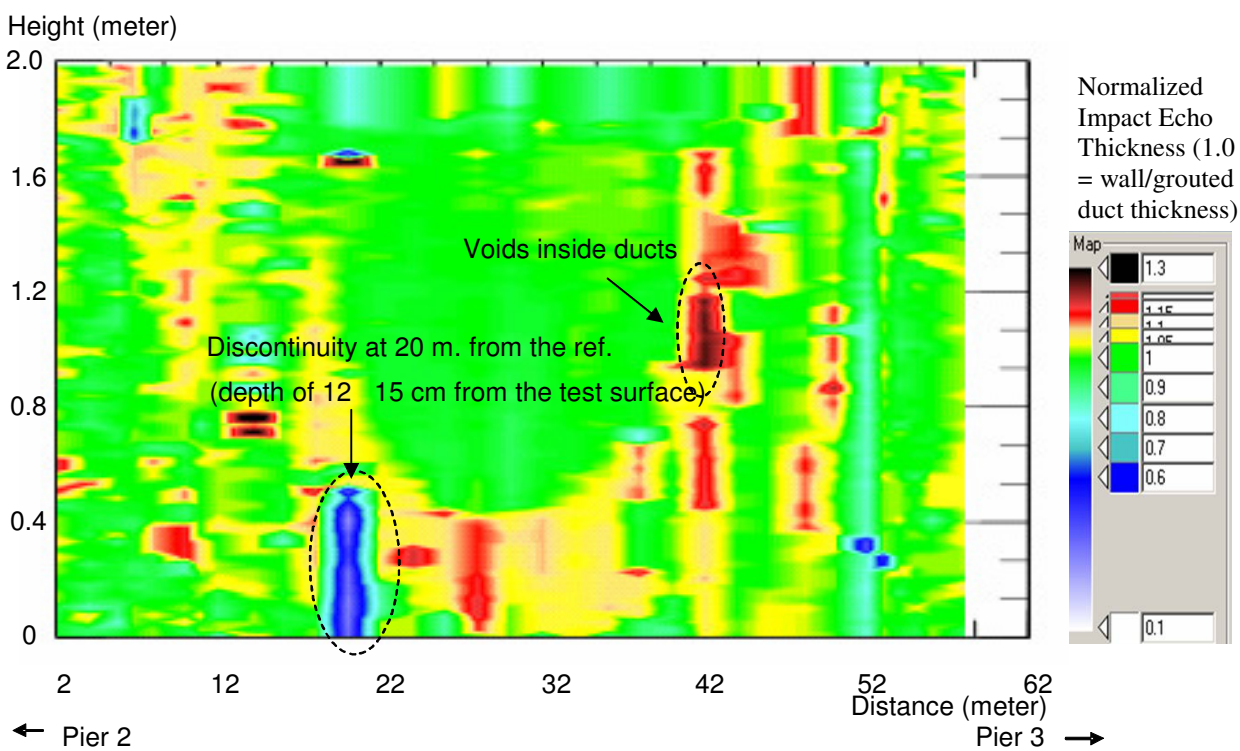

Figure 1. 3D Normalized Thickness Tomogram results for Bridge Web Wall (General Condition)

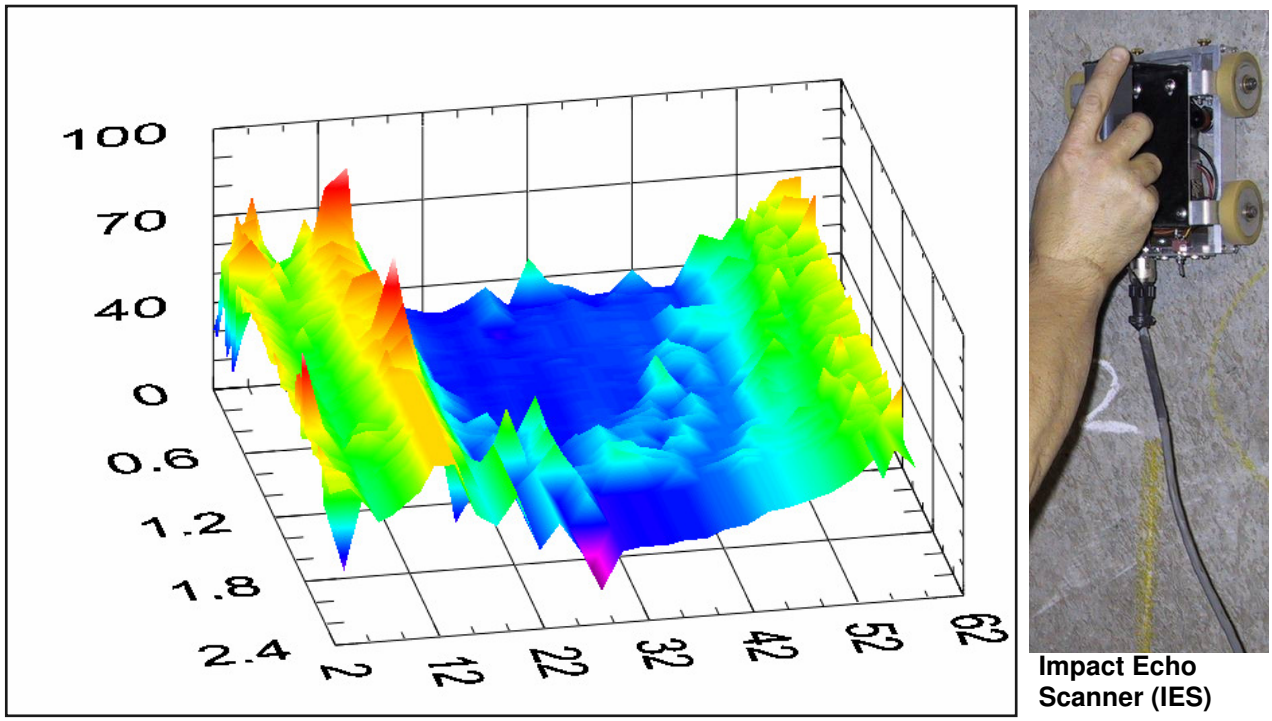

Figure 2. 3-D IE Scan Display showing thickened ends and possible thicker voided duct areas for 1.8 m vertical scans of wall over 2-62 m length with vertical thickness echo scale of 100 cm (1 m)

BRIDGE DECK SCANNING WITH IMPACT ECHO METHOD

A vehicle-mounted Bridge Deck Scanner using Impact Echo (BDS-IE) for evaluation of concrete deck integrity was recently researched under an NCHRP IDEAS grant (6) and found to the most accurate at detecting deck delaminations due to corrosion. The focus of the research was on improved evaluation of concrete deck integrity conditions (delamination, void, cracking, concrete quality, etc.) and impact echo, acoustic sounding, surface wave, slab impulse response and ground penetrating radar were all studied.

Project Background and Investigation Overview

A nondestructive evaluation (NDE) investigation and condition assessment of a concrete bridge deck was performed in early 2010 by Olson Engineering. The Impact Echo testing was performed using the Bridge Deck Scanner (BDS-IE) which performs Impact Echo testing while slowly being rolled (~1 mph) along the test surface (see Figure 3). The BDS-IE unit consists of two transducer wheels (approximately 1 ft in diameter) which use 6 displacement transducers around the wheels to measure the IE resonant echoes induced by 6 on-board automated solenoid impactors on each wheel. The Olson Instruments Freedom Data PC based system performs an Impact Echo test at 6-inch intervals with each testing wheel. Since the BDS-IE unit consists of two testing wheels, 2 lines of IE data are acquired simultaneously since the wheels are offset 30 degrees to provide for staggered testing every 3 inches by the left and right wheels. The density of IE testing is therefore every 6 inches in the longitudinal direction of the bridge with test lines conducted the length of the bridge that are spaced 1 foot apart across the width of the bridge. This test pattern provided for an IE test of every 0.5 sq ft of the nominally 8 inch thick bridge deck.

The BDS-IE testing was performed by towing the unit the full length of the bridge deck as well as over the concrete approach slabs at either end of the bridge. The approach slabs are 12 inches thick and are each 20 feet in length. Therefore the total tested length was approximately 370 feet.

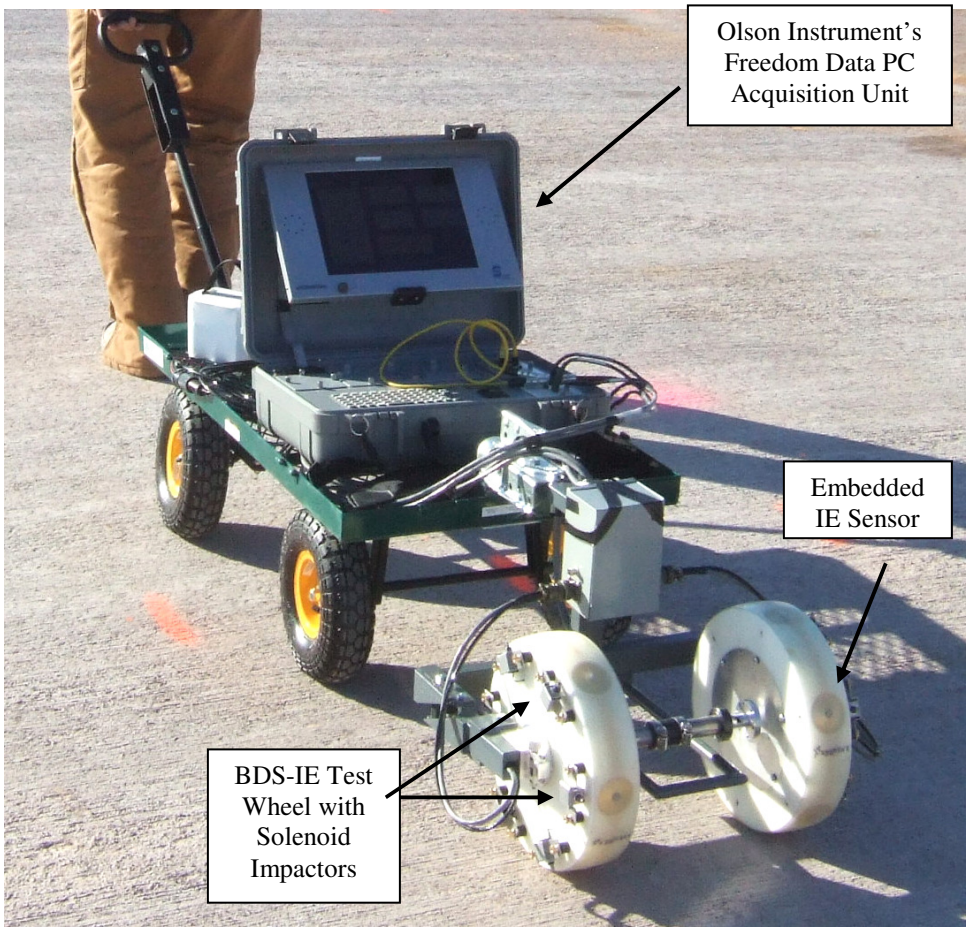

Figure 3. Photograph of Olson Instruments BDS-IE system on rough finish Concrete Deck

Nondestructive Evaluation Results from Bridge Deck Scanner – Impact Echo (BDS-IE)

In total, approximately 25,000 separate IE tests were performed on the bridge deck and approach slabs in about 5 hours at a speed of 1 to 1.5 mph. An impact echo concrete compression wave velocity of 13,500 ft/sec was used for all thickness calculations. This compressional wave velocity (which is slightly above average reflecting the concrete compressive strength of ~ 8,000 psi) was back-calculated, assuming the concrete bridge deck was nominally 8 inches thick. The impact echo data was analyzed by determining the resonant frequency of the concrete structure at each test point. The resonant frequency is directly related to the deck thickness per Equation 1, which was calculated in inches. Changes in the concrete condition of the structure are identified by shifts in the resonant frequency (a lower resonant frequency indicates either thicker concrete or honeycomb/void due to a lower stiffness of the deck) or the presence of multiple resonant frequencies indicative of internal cracking.

The Impact Echo data was processed by applying a time domain rectangular window to remove any noise that may have occurred near the time of the impact. The data was then digitally filtered with a 4 pole Butterworth high-pass filter at 4,000 Hz to remove low frequency rolling noise inherent to the system. Note that the typical resonant thickness echo frequency of the concrete bridge deck was approximately 10,000 Hz. These processing steps allow the resonant frequency of the concrete deck to be easily identified. Figure 4 displays example data from a test line performed with the BDS-IE system on the tested bridge.

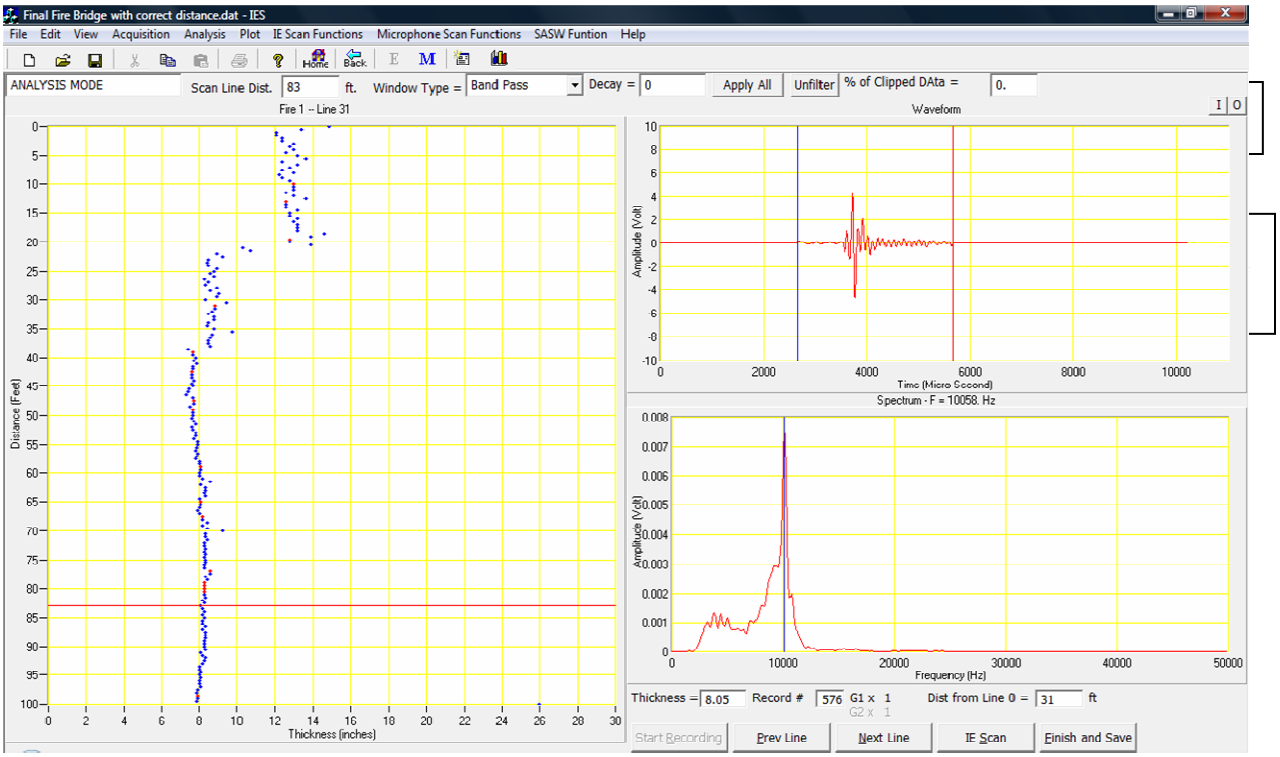

Figure 4. Example Impact Echo Results from the Olson Instruments BDS-IE system. Thickness echo data shown on the left is for the first 100 feet of data from the north end of the bridge at a distance of 31 feet west of the east parapet wall.

Each test line acquired was analyzed as described above and combined to create a plan view image result of the bridge deck as presented in Figure 5. The variation in apparent concrete thickness from the impact echo results is displayed as different colors. Sound concrete conditions will appear as thicknesses near the design thickness. Poorly consolidated, honeycombed or voided concrete will have a lower resonant frequency due to the decreased deck stiffness/density and will therefore appear thicker than expected. Cracking and deeper delaminations will generally appear thinner than the design thickness; a shallow delamination will produce a high amplitude, ringing, low-frequency response indicative of the flexural vibrations of the concrete (corresponds to the hollow, drummy sound that occurs in acoustic chain dragging or hammer sounding). Note that the concrete girders, piers and diaphragm walls between girders also create an apparent increase in thickness in the data results. However, these features can be accounted for spatially with respect to the results and are not considered defects in Figure 5.

The plan view color plot of the results displayed in Figure 5 shows the bridge deck to be of sound condition with a calculated deck thickness near the expected design thickness of 8 inches. As expected, the north and south approach slabs appear thicker than the bridge deck. Also appearing thicker are the tested areas immediately above the concrete girders and pier caps. The diaphragm walls were not apparent in the IE data. Besides the girders, approach slabs, pier cap, and diaphragm walls, there are notable areas dispersed throughout the image of Pink (thinner than 7.5 inches) and Yellow (8.5 – 9.5 inches). The analysis does not identify these areas as defects for several reasons. First, during analysis it was noted that these areas were due to gradual changes in resonant frequency, indicative of slightly varying concrete deck thickness or varying material properties (concrete velocity). Second, the Green or "Sound" areas are within 0.5 inches of the 8 inch design thickness or 6.25%. The Yellow areas represent thickness values from 6.25 – 18.75 % thicker than the design thickness. Olson Engineering's experience has shown that significant honeycombed or otherwise poorly consolidated concrete typically has calculated thickness values +25% greater than the expected echo thickness of 8 inches (Red areas). Therefore, upon detailed review of all BDS-IE data, the bridge deck is considered sound with no significant internal concrete anomalies or defects indicative of honeycomb/void or other flaws.

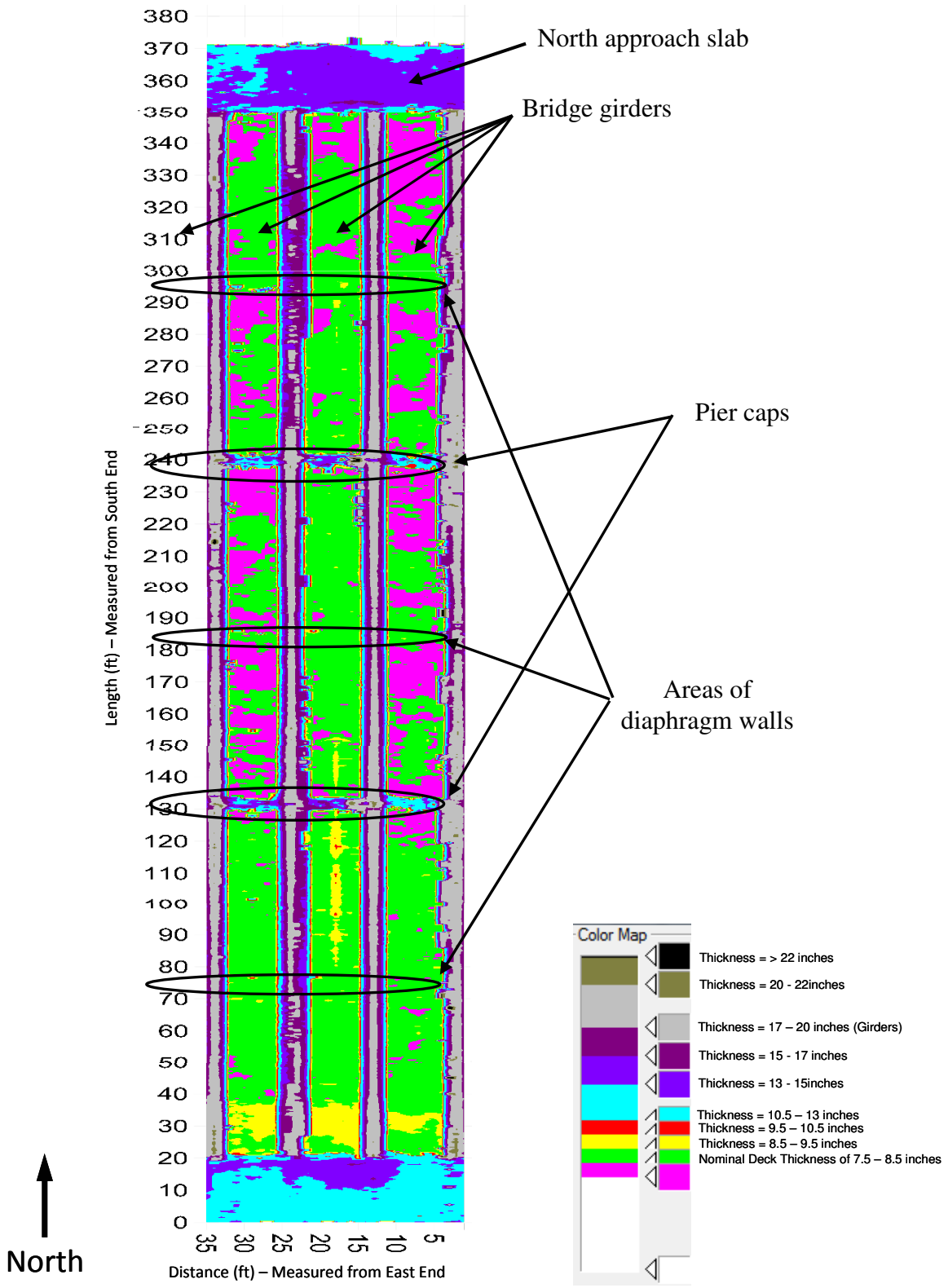

Figure 5. Impact Echo Results from the BDS-IE system. Results are displayed in terms of deck/approach slab thickness (inches) which relates to the deck/slab resonant echo frequency.

The plan view color plot of the results displayed in Figure 5 shows the bridge deck to be of sound condition with a calculated deck thickness near the expected design thickness of 8 inches. As expected, the north and south approach slabs appear thicker than the bridge deck. Also appearing thicker are the tested areas immediately above the concrete girders and pier caps. The diaphragm walls were not apparent in the IE data. Besides the girders, approach slabs, pier cap, and diaphragm walls, there are notable areas dispersed throughout the image of Pink (thinner than 7.5 inches) and Yellow (8.5 – 9.5 inches). The analysis does not identify these areas as defects for several reasons. First, during analysis it was noted that these areas were due to gradual changes in resonant frequency, indicative of slightly varying concrete deck thickness or varying material properties (concrete velocity). Second, the Green or "Sound" areas are within 0.5 inches of the 8 inch design thickness or 6.25%. The Yellow areas represent thickness values from 6.25 – 18.75 % thicker than the design thickness. Olson Engineering's experience has shown that honeycombed or otherwise poorly consolidated concrete typically has calculated thickness values +25% greater than the expected echo thickness of 8 inches (Red areas). Therefore, upon detailed review of all BDS-IE data, the bridge deck is considered sound with no significant internal concrete anomalies or defects indicative of honeycomb/void or other flaws.

IMAGING BY INTERFEROMETRIC SURVEY – STRUCTURES (IBIS-S) FOR BRIDGES

IBIS-S is an innovative microwave radar sensor, developed by the IDS company of Pisa, Italy in collaboration with the Department of Electronics and Telecommunication of the Florence University. It is able to simultaneously measure the displacement response of several points belonging to a structure with accuracy on the order of a hundredth of a millimeter. IBIS-S can be used to remotely measure structural static deflections as well as vibrations to identify resonant frequencies and mode shapes and was recently compared with GPS results on the suspension cable and steel truss Manhattan Bridge in New York City (7). In addition to its non-contact feature, the new vibration measuring system provides other advantages including quick set-up time, a wide frequency range of response and portability.

IBIS-S Radar System Description

The IBIS-S system is based on interferometric (8) and wide band waveform principles. It is composed of a sensor module, a control PC and a power supply unit. The sensor module (Figure 6) is a coherent radar unit, generating, transmitting and receiving the electromagnetic signals to be processed in order to compute the displacement time-histories of measurement points belonging to the investigated structure. The sensor module, including two horn antennas (Figure 6) for transmission and reception of the electromagnetic waves, exhibit a typical super heterodyne architecture. The base-band section consists of a Direct Digital Synthesis (DDS) device to obtain fast frequency hopping. A tuneable sine wave is generated through a high-speed D/A converter, reading a sine lookup table in response to a digital tuning word and a precision clock source. The radio-frequency section radiates at a center frequency of 17.2 GHz with a maximum bandwidth of 300 MHz; hence, the radar is classified as Ku-band, according to the standard radar-frequency letter-band nomenclature from IEEE Standard 521-1984. A final calibration section provides the necessary phase stability; design specifications on phase uncertainty are suitable for measuring short-term displacements with a range uncertainty lower than 0.01 mm (0.0004 inches). The sensor module is installed on a tripod equipped with a rotating head, allowing the sensor to be orientated in the desired direction (Figure 6). The module has an USB interface for connection with the control PC and an interface for the power supply module.

The control PC is provided with the software for the system management and is used to configure the acquisition parameters, store the acquired signals, process the data and view the initial results in real time. With a maximum operational distance (for minimum 40Hz vibration sampling frequency) of 500 m, a maximum sampling frequency of 200 Hz, and a displacement sensitivity of 0.01 mm, the IBIS-2 can be operated in all weather conditions. Finally, the power source is a 12 V battery.

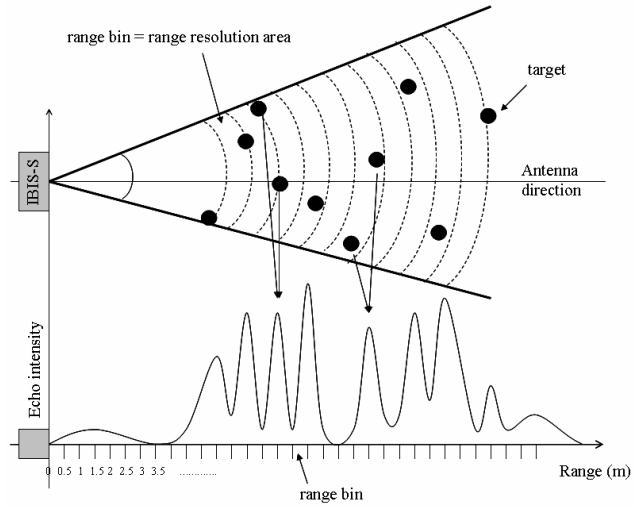

Figure 6. View of the new *IBIS-S* sensor **Figure 7. Radar range resolution concept**

IBIS-S Radar Basic Principles

The ability to determine range (i.e. distance) by measuring the time for the radar signal to propagate to the target and back is surely the distinguishing and most important characteristic of radar system. Two or more targets, illuminated by the radar, are individually detectable if they produce different echoes. The resolution is a measure of the minimum distance between two targets at which they can still be detected individually. The range resolution refers to the minimum separation that can be detected along the radar's line of sight. The IBIS-S system is capable of providing range resolution, i.e. to distinguish different targets in the scenario illuminated by the radar beam. Peculiarly, this performance is reached by using the Stepped-Frequency Continuous Wave (SF-CW) technique. Pulse radars use short time duration pulses to obtain high range resolution. For a pulse radar, the range resolution Δr is related to the pulse duration τ by the following (8):

$$\Delta r = \frac{c\tau}{2} \tag{2}$$

where c is the speed of light in free space. Since (see e.g. (9)) $\tau = 1/B$, the range resolution (1) may be expressed as:

$$\Delta r = \frac{c}{2B} \tag{3}$$

Eq. (3) highlights that range resolution increases (corresponding to a smaller numerical value of Δr) as the frequency bandwidth of the transmitted electromagnetic wave increases; hence, closely spaced targets can be detected along the radar's line of sight. The SF-CW technique exploits the above concept to provide the IBIS-S sensor with range resolution capability.

The SF-CW technique is based on the transmission of a burst of N monochromatic pulses, equally and incrementally spaced in frequency (with fixed frequency step of Δf), within a bandwidth B:

$$B = (N-1)\Delta f \tag{4}$$

The N monochromatic pulses sample the scenario in the frequency domain similarly to a short pulse with a large bandwidth B. In a SF-CW radar, the signal source dwells at each frequency $f_k = f_o + k\Delta f$ (k=0,1,2, …, N–1) long enough to allows the received echoes to reach the receiver. Hence, the duration of each single pulse (Tpulse) depends on the maximum distance (Rmax) to be observed in the scenario:

$$T_{pulse} \geq \frac{2R_{max}}{c} \tag{5}$$

In the IBIS-S sensor, the SF-CW radar sweeps a large bandwidth B with a burst of N single tones at uniform frequency step, in order to obtain a range resolution of 0.50 m; in other words, two targets can still be detected individually by the sensor if their relative distance is greater than 0.50 m. The range resolution area is termed range bin. The radar continuously scans the bandwidth at a rate ranging up to 200 Hz, so that the corresponding sweep time Δt of 5 ms is in principle well suitable to provide a good waveform definition of the displacement response for a civil engineering structure.

At each sampled time instant, both in-phase and quadrature components of the received signals are acquired so that the resulting data consists of a vector of N complex samples, representing the frequency response measured at N discrete frequencies. By taking the Inverse Discrete Fourier Transform (IDFT) the response is reconstructed in the time domain of the radar: each complex sample in this domain represents the signal (echo) from a range (distance) interval of length cTpulse/2.

The amplitude range profile of the radar echoes is then obtained by calculating the magnitude of each bin of the IDFT of acquired vector samples. This range profile gives a one dimensional map of scattering objects in the viewable space in function of their relative distance from the equipment. The concept of range profile is better illustrated in Figure 7, showing an ideal range profile obtained when the radar transmitting beam illuminates a series of targets at different distances and different angles from the system. The peaks in the lower plot of Figure 7 correspond to "good" measurement points and the sensor can be used to simultaneously detect the displacement and the transient response of these points. These good reflective points could be either given by the natural reflectivity of some points belonging to the structure or by some simple passive metallic reflectors applied on it. Once the image of the scenario illuminated by the radar beam has been determined at uniform sampling intervals Δt, the displacement response of each target detected in the scenario is evaluated by using the Differential Interferometric technique (see eq. 6, below); this technique is based on the comparison of the phase information of the back-scattered electromagnetic waves collected in different times.

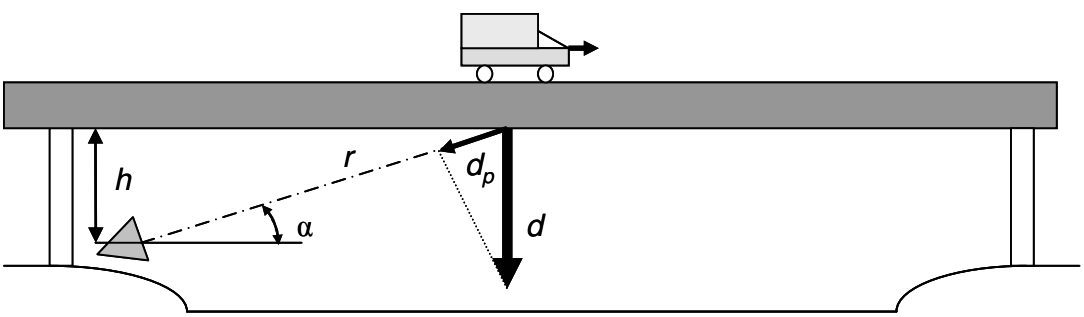

Figure 8. Radial displacement vs. projected displacement

Generally speaking, when a target surface moves with respect to the sensor module (emitting and back-receiving the electromagnetic wave), at least a phase shift arises between the signals reflected by the target surface at different times. Hence, the displacement of the investigated object is determined from the phase shift measured by the radar sensor at the discrete acquisition times. The radial displacement dp (i.e. the displacement along the direction of wave propagation) and the phase shift $\Delta\varphi$ are linked by the following:

$$d_p \propto \frac{\lambda}{4\pi}\Delta\varphi \tag{6}$$

where λ is the wavelength of the electromagnetic signal.

The sensor module emits a series of electromagnetic waves for the entire measurement period, and processes phase information at regular time intervals (up to 5 ms) to find any displacement occurring between one emission and the next. It is worth emphasizing that the interferometric technique provides a measurement of the radial displacement of all the range bins of the structure illuminated by the antenna beam; once the radial displacement *dp* has been evaluated, the vertical displacement *d* can be easily found by making some geometric projection, as shown in Figure 8.

Interferometric Radar Demonstration on Bridge

A demonstration test of the IBIS-S system was performed on a post-tensioned, curved, box girder bridge in Golden, Colorado (see Figure 9). The primary objective of the demonstration was to measure the deflection time-histories and maximum deflections of the bridge under normal automobile and truck traffic loading. The IBIS-S system was deployed below the bridge superstructure, illuminating 5 metallic reflectors that had to be installed (due to the smooth concrete surfaces) along the bridge side at the same time (each one at about a 7.5 m spacing). The test demonstration required one-half of a field day, which included field set-up time and all data acquisition. Due to the non-contacting nature of the system and operational range, all testing was performed with no traffic disruption and minimal field support requirements.

Figure 9– IBIS-S Unit at Post-Tensioned Segmental Concrete Bridge

Each of the corner steel sheet metal reflectors produces a sharp peak on the IBIS-S range profile and therefore a good quality data point whose displacement can be measured by analyzing the phase variations with the differential interferometric technique. Figure 10 presents the IBIS-S Power Profile: a high level of backscattered signal in the range bin in which a crossing beam is located gives a high Signal to Noise Ratio and therefore high accuracy in the measurement of the displacement.

The vertical displacements of the five metallic reflectors installed on the bridge side during the dynamic test are presented in Figure 11 which shows the resulting displacements from the passage of a testing truck and other vehicles over the bridge deck. The maximum measured peak to peak displacement at mid-span is 2.26 mm. Vertical velocity vibration amplitudes of the measurement points range from +/- 4 mm/sec, depending on truck speed. Both displacement and velocity spectrums show 6 sharp frequency peaks at 1.3, 2.05, 2.45, 2.95, 3.35 and 3.55 Hz, corresponding to the structural resonance modes. The first three should correspond to mainly flexional modes while the second three should be related to mainly torsional modes. Further analysis could be performed by importing the IBIS-S Displacement Time Series into specific software for dynamic structural engineering to evaluate, for example, the vibration mode shapes.

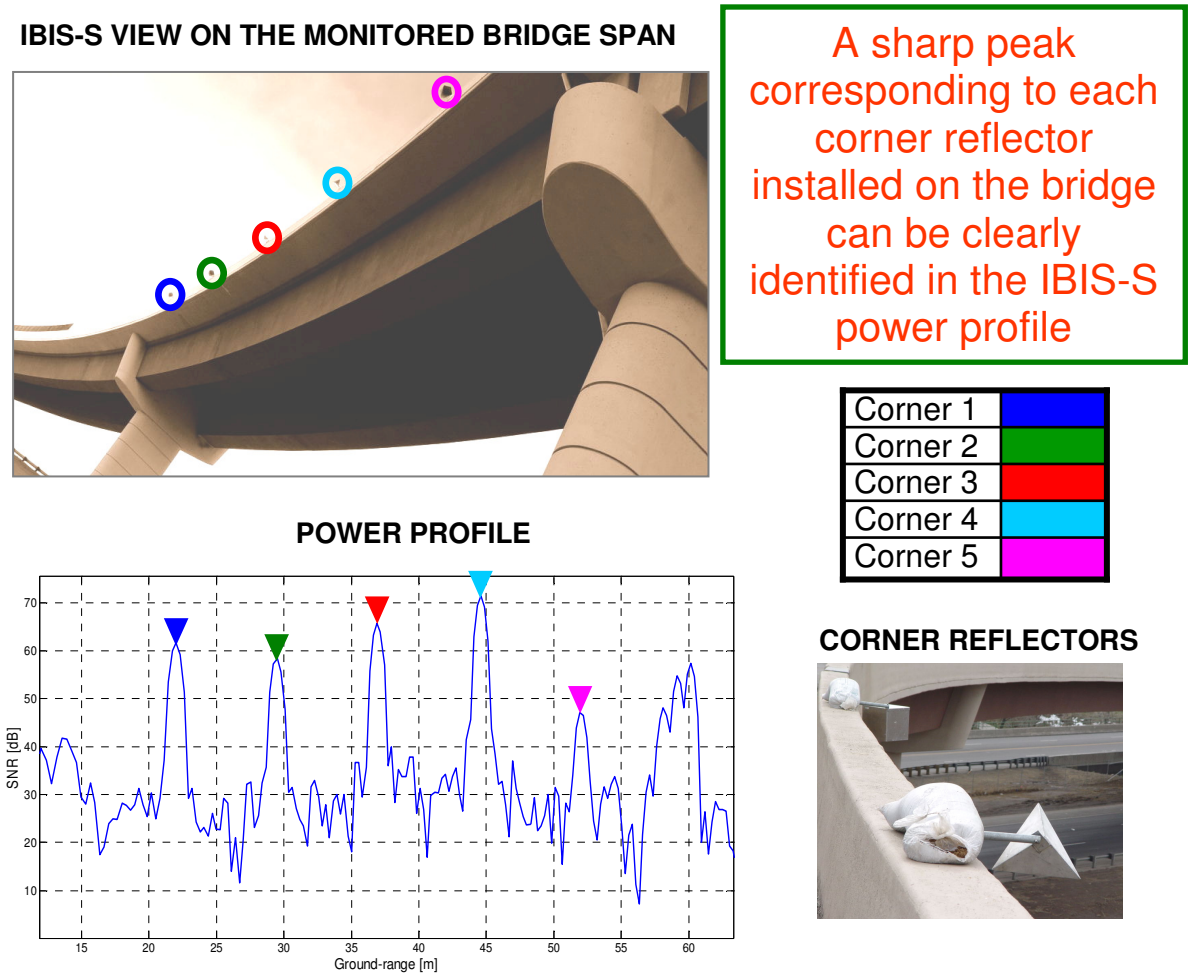

Figure 10. Portion of the IBIS-S Power Profile and Corner Reflectors

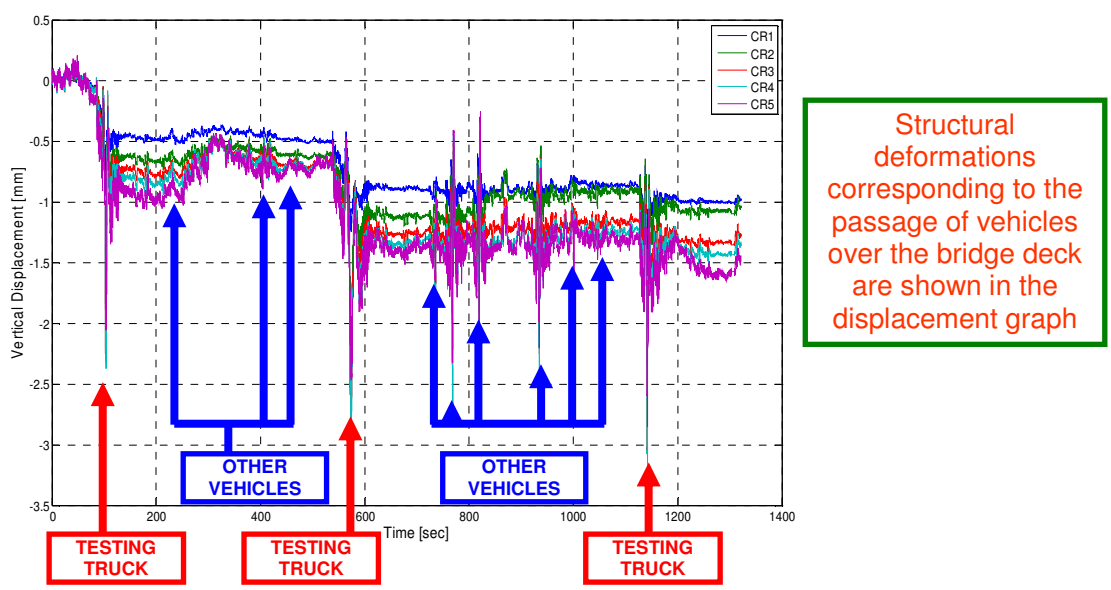

Figure 11. Vertical displacements of the five passive metallic reflectors installed on the bridge integrally cast concrete guardrail caused by passing vehicles and truck (55,000 lbs)

CONCLUSIONS

Impact Echo Scanning (IES) has been found to provide accurate detection of poorly grouted/voided ducts in post-tensioned bridges and can be readily applied in hand-scanning of large areas of bridge walls and slabs. Recent research and consulting has built on the IES method to provide a Bridge Deck Scanner (BDS-IE) that is capable of providing high quality data on concrete bridge decks for accurate evaluation of delamination/void/honeycomb/cracking conditions. The BDS-IE operates at about 1-1.5 mph and is typically used to provide for test resolution of 0.5 sq ft per test. The microwave radar based Interferometric By Imaging Survey system for structural health monitoring of displacements and vibrations can operate up to 100 Hz and measure displacements in a line of site fashion with an accuracy up to 0.01 mm (0.0004 inch). The IBIS-S system can be rapidly deployed for short-term displacement and vibration monitoring. This provides for short-notice, economical static and dynamic load tests as well as for measurement of operating displacements and ambient vibration measurements needed for modal vibration analyses.

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